Vertisol Crack Extent Associated with Gilgai and Soil Moisture in the Texas Gulf Coast Prairie

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Long-term observations of in situ crack formation and closure in shrink-swell soils are rare, but important to understanding hydrology in shrink-swell soils. To analyze spatial and temporal variability of crack development in a Vertisol with gilgai, soil cracks were measured on a 100-m^2 area of Laewest clay (fine, smectitic, hyperthermic Typic Hapludert) with native tallgrass vegetation on 42 dates from 1989 to 1998. Our objectives were to (i) report the distribution of Vertisol cracking across gilgai microtopography; (ii) estimate crack depth as a function of crack width considering gilgai; (iii) investigate the relationship of surface cracking and soil moisture considering gilgai and hysteresis. All surface cracks were mapped on scaled diagrams with width categorized, and some crack depth measured. Gravimetric soil moisture corresponding to crack measurements was measured on 18 dates, and on an additional 32 dates without crack measurements. Drying, wetting, and uniform soil moisture conditions were classified from the difference in soil moisture from 10- to 25-cm depths. Microtopography was quantified using a digital elevation model. Results showed that crack area density was greatest on microhighs and microslopes, though microlows had the largest cracking potential. The linear correlation between crack depth and width was moderately strong (r^2 = 0.5), and not affected significantly by gilgai and hysteresis. However, taking hysteresis into account improved the linear regression models of crack area density versus soil moisture (up to r^2 = 0.69) on both microhighs and microlows. Antecedent soil moisture seemed to impact in situ crack area density. Further field studies are recommended.

PEDOLOGY

Shrinking and swelling of clay-rich soils create dynamic crack formation which changes landscape hydrology and facilitates rapid transport of water pollutants into the soil and groundwater (Bouma et al., 1981; Lin et al., 1997). Vertisols, which have a well-defined cracking structure when dry, cover approximately 65 000 km^2 in humid and subhumid climatic conditions along the coastal plain of Texas (Coulombe et al., 1996b). Since cracking soils cover large areas in the landscape and affect soil hydrology, understanding the process of cracking is important to mapping the spatial distribution of cracks and to modeling the temporal dynamics of surface hydrology.

Soil cracking behavior in Vertisols is particularly complex because Vertisols can form their own microtopography, gilgai, which consists of circular mounds or linear ridges and depressions. This gilgai affects the shrink-swell soil properties at microscopic and pedon scales and consequently at the landscape scale (Puentes et al., 1992; Coulombe et al., 1996a). In humid climates and relatively flat landscape, such as in the Texas Gulf Coast Prairie, formation of round gilgai is most typical (Nordt et al., 2004). Gilgai microtopographical features are associated

with differences in soil properties such as fine clay, organic matter, carbonates, and salt content (Coulombe et al., 1996a). According to general trends summarized by Wilding et al. (1990), carbonates, exchangeable bases, cohesive strength, and pH are found to be greater in microhighs. On the other hand, coefficient of linear extensibility (COLE), specific surface area, shrinkage percentage, cracking width and depth, and moisture are reported greater in microlows. Organic C, electrical conductivity and exchangeable Na percentage are usually greater in microlows, but reverse trends have also been reported.

The literature does not agree about crack development on microtopography formations. On a Burleson clay (fine, smectitic thermic Udic Haplustert) in Texas, Spotts (1974) observed the maximum change in soil expansion and contraction 45 cm below the surface of microhighs, indicating that the shrink-swell was greater in microhighs. In a Houston Black soil of Texas, Amidu and Dunbar (2007) also found indications by measuring variations of electrical resistivity that microhighs dried out faster than microlows. Additionally in Boorook, Victoria, Australia, Knight (1980) found approximately twice as many cracks per unit area in mounds (microhighs) of a salt-affected Vertisol than in shelves or depressions (microlows). On the contrary, Thompson and Beckman (1982) observed more and deeper cracks on microlows of Black Earth following an early phase of more intense cracking in microhighs, and speculated that denser vegetation on microlows would desiccate soils faster and deeper than in microhighs. In addition, the highest noncarbonate clay content and specific surface area are the highest in microlows resulting in larger shrink-swell potential than in microhighs (Wilding and Tessier, 1988).

Additionally to differences in soil morphological features, gilgai microtopography contributes to spatial and temporal

differences in soil moisture distribution in the field. Sloping terrain can route surface runoff water into the microlows, contributing to spatial variability in soil drying, cracking, and infiltration. This surface routing of water adds potential for cracking to vary spatially through runoff and runon in microtopography, and temporally by high intensity rainfall being distributed differently from low intensity rainfall (Bradley et al., 2007). High intensity rainfall is expected to generate runoff, hence the distribution over the microtopography would be more variable, while low intensity rainfalls might have a relatively more uniform infiltration and redistribution. Due to possible multiyear variability of rainfall, one might expect a 2- to 3-yr observation of soil cracking to have different results than longer observations that may cover more extreme weather events. For example, the interannual El Nino/Southern Oscillation shows high peaks at 2 to 7 yr in temporal distribution of precipitation (Gurdak et al., 2007; IPCC, 2007).

Spatial and temporal differences in soil moisture distribution of Vertisols in the field may contribute to variability of soil water hysteresis. Soil water hysteresis creates difference in water retention under wetting and drying conditions (Mitchell and Mayer, 1998; Lal and Shukla, 2004). Alternate wetting-drying can cause changes in the soil structure and pore-size distribution, and consequently in hysteresis. In turn, the difference in retained water may influence the magnitude of shrinking-swelling conditions under different wetting or drying conditions (Tessier, 1990). Thus complex shrinking-swelling mechanisms in a Vertisol landscape with gilgai may also be influenced by soil water hysteresis, but this effect has not been documented in situ.

Direct measurements on cracking of Vertisols in field conditions are limited. To estimate mean crack dimensions, surface crack width, length, and vertical depth have been measured along transects at fixed or randomly selected locations (Zeil el Abedine and Robinson, 1971; Yaalon and Kalmar, 1984; Dasog et al., 1988; Ringrose-Voase and Sanidad, 1996), and in small plots (about 1 m^2) in repetitions (Dasog and Shashidhara, 1993; Yassoglou et al., 1994; Bandyopadhyay et al., 2003). These in situ measurements included different land use, irrigation, tillage, and nutrient management systems. Although transects or small area plots were useful for estimating mean values of crack dimensions; nevertheless, spatial and temporal processes of variable crack pattern of Vertisols with gilgai microtopography is likely to be better investigated in larger continuous study area covering several microhighs and microlows.

Despite numerous studies highlighting distinct differences in morphology and water movement across gilgai features, only Knight (1980) measured crack dimensions in an extensive study site with gilgai, and reported observations of surface crack area density, according to gilgai microtopography. However, the study was conducted only on one occasion. On a Vertisol, Cheng and Pettry (1993) measured horizontal and vertical soil movements in situ over 20 mo; however, no actual cracks measurements were recorded, and no obvious sign of gilgai microtopography was found. Monitoring temporal variability of measured Vertisol cracking in respect to gilgai has not been documented.

The time span of most in situ investigations related to soil shrink-swell is relatively short. Most of the studies conducted in natural field conditions lasted less than a year (Knight, 1980; Spotts, 1974; Thompson and Beckman, 1982; Yaalon and Kalmar, 1984; Hallaire, 1984; Dasog et al., 1988; Klich et al., 1990; Bronswijk, 1991; Dasog and Shashidhara, 1993; Coquet, 1998; Amidu and Dunbar, 2007), a few studies monitored processes between 1 and 3 yr (Cheng and Pettry, 1993; van Dam, 2000; Kirby et al., 2003; Arnold et al., 2005; Das Gupta et al., 2006), and none covered more than 3 yr. In more controlled irrigated field conditions, shrink-swell studies were conducted within a year (Mitchell and van Genuchten, 1993; Yassoglou et al., 1994; Tuong et al., 1996; Ringrose-Voase and Sanidad, 1996; Favre et al., 1997; Coquet et al., 1998). In 1- to 3-yr experiments, relatively short-term shrink-swell processes are measured. However, influence of weather events with longer frequencies may not be represented well. Shrinking-swelling of Vertisols as a function of soil moisture with spatial and temporal variability associated with gilgai in field conditions remains poorly understood.

To document close-interval spatial variability of a Vertisol with gilgai microtopography in Udic soil moisture regime, a case study was developed on 100 m^2 in the Texas Gulf Coast Prairie (Wilding et al., 1990). The long-term study was designed to improve understanding of genesis, classification and management of Vertisol systems and sampling schemes for better characterization. The underlying research questions of the study included: where desiccation cracks start and develop in greater extent on microhighs or on microlows; how the relationship of crack width and depth is affected by gilgai microtopography; and how temporal variation of cracking on gilgai depends on soil water content. In this paper, our specific objectives were to report on (i) investigating the distribution of Vertisol crack area density across gilgai microtopography; (ii) estimating total crack depth as a function of crack width considering gilgai microtophraphic location; and (iii) empirically analyzing surface crack area density and gravimetric soil moisture relationship on microhigh and microlow, while accounting for soil drying and wetting.

MATERIALS AND METHODS
Study Site Description

A 10-m by 10-m plot of native prairie was selected on Laewest clay as a representative Vertisol of the Central Texas Gulf Coast region. The site selection method and characteristics of the region are described in detail by Wilding et al. (1990). The soil was classified first as Lake Charles clay and was changed later to Laewest clay; fine, smectitic, hyperthermic Typic Hapluderts (Soil Survey Staff, 1999) developed on gray calcareous clayey alluvium of the Pleistocene-age Beaumont formation (Nordt et al., 2004; 2006). The site was located at 28° 39' 46" N, 96 º 46' 20" W and 12 m general elevation in Victoria County, Texas (USA).

Typical gilgai including mounds and ridges as microhighs, and small depressions as microlows was well expressed. The microlows were 10 to 25 cm deep, 2 to 3 m across and about 6 to 7 m apart and occurred in a relatively regular pattern. Soil in microlows was typically black and noncalcareous, while soil of the microhighs was grayish and calcareous. Grayish calcareous, clayey subsoil rose to the surface to form subsurface chimneys, and calcareous puffs were sometimes exposed at the surface. A gray intermediate calcareous clay zone dominated the area. The morphology and terms of surface and subhorizon features in Laewest clays and other similar Central Texas Gulf Coast

region Vertisols are illustrated in details by Miller and Bragg (2007). The vegetation cover was native tallgrass prairie vegetation dominated by little bluestem [*Schizachrium scopariu* (Michx.) Nash], Indiangrass (*Sorghastrum nutan* L. Nash), and brownseed paspalum (*Paspalum plicatulum* Michx.). Detailed vegetative composition for microhigh and microlow positions was reported in Wilding et al. (1990).

Precipitation data were collected regularly at a weather station at Victoria Regional Airport, 16 km north of the site (http://cdo.ncdc.gov/pls/plclimprod/poemain.cdobystn?dataset =DS3240&StnList=419364, verified 19 Mar. 2009). During the 10 yr of observation, the 30-yr average of annual precipitations for the region increased from 940 to 1019 mm indicated by measurements of 1961–1990 and 1971–2000, respectively (USDA Natural Resources Conservation Service, 2002). The yearly and monthly mean precipitations, along with their normal thresholds were found in the WETS (Wetlands Determination) table of the National Water and Climate Center (USDA Natural Resources Conservation Service, 1995). The normal precipitation range was defined as the 30th and 70th percentile of a 2-parameter γ distribution fitted to the precipitation data of 1971–2000 (Sprecher and Warne, 2000; USDA Natural Resources Conservation Service, 1995, 2000).

On-site Measurements and Soil Sampling

During the 10-yr period, soil crack measurements were taken on 42 dates as follows: two in 1994, 1996, and 1998, three in 1991, 1995, and 1997, four in 1989, seven in 1992 and 1993, and nine in 1990. The minimum time between measurements was 10 d between August 28 and September 7 in 1990. On each date, surface width, length, and location of all cracks of the study site were measured by using a 1-m × 1-m frame with a grid of 0.1-m cell size placed on the soil surface. Crack locations were plotted on engineer graphing paper on a 0.0254 to 1.0-m scale. On each diagram, crack widths were grouped into categories with limits of 0.5, 1, 2, 5, and 7 cm, and were recorded with color-codes on the diagram; the mid-value of each category was used in the analysis. Locations for crack depth measurements were selected to characterize the deepest cracks. The vertical crack depth relative to the surface was measured with a pointed steel tape (6.35-mm wide and 0.79-mm thick) and recorded with the exact width. Special landscape features, such as calcareous puffs of chimneys, fire ant and crayfish mounds were also plotted on the diagrams. The site was mowed and raked six times during the10-yr period when the grass was taller than 15 cm, to make the cracks visible and measurable.

The soil profiles were characterized according to Soil Taxonomy from a 2-m deep trench transecting microhighs and microlows, about 5 m from the crack measurement site (Soil Survey Staff, 1990; Wilding et al., 1990). Soil samples were collected from a microlow and microhigh of the trench in September 1988, and were analyzed for particle-size distribution (pipette method), fine clay (centrifuging and pipette method), organic C (modified Walkley-Black wet combustion method), inorganic C (HCl treatment), and COLE (clod method) using USDA-NRCS standard procedures (Soil Survey Staff, 1984).

Soil moisture was measured gravimetrically in two to three replicates at 10-, 25-, 50-, 75-, and 100-cm depth on microhighs and microlows adjacent to the site. Moisture samples were collected on 18 dates within 1 to 2 d of crack diagrams with no or only trace of precipitation and on an additional 32 dates without crack measurements. Elevation was measured on 0.5-m increment transects that were 2-m apart with additional measurements at high and low points using standard surveying techniques.

Procedures in a Geographic Information System

Crack diagrams were scanned with a 157 pixel cm^{-1} resolution and rectified to Universal Transverse Mercator coordinate system. Polylines, defined as crack segments between junctions or end points and/or changing crack width, were digitized in ArcView 9.0 (Environmental Systems Research Institute, 2005) and analyzed in ArcGIS. A digital elevation model (DEM) with 0.05-m cell size was generated using discretized thin plate splines from the measured elevation points (Wahba, 1990). Several points in the vicinity of the site were also included in the calculation to improve the spline calculations for the boundaries. Slope, plain-curvature, and slope-curvature were calculated for each cell, and from these, microtopography categories were determined by using raster calculator in Spatial Analyst. Microlows were defined as cells with ≤3% slope that are concave, convergent, or divergent, and cells of 3 to 5% slope, that are concave and convergent. Microhighs associated with calcareous puffs were defined as cells with ≤3% slope that are convex, convergent or divergent, and slope >3% that are convex and divergent. All other cells were classified as microslopes (Fig. 1).

Polylines were clipped according to masks of the three microtopography categories. Length of polylines was calculated by using Hawth's Tool 3 (Beyer, 2004). Coordinates of each midpoint were determined after clipping by using ET GeoWizards 9.4.1 (Tchoukanski, 2005). Both length and midpoint coordinates of crack segments were added to the attribute table of each crack diagram. Crack area density was calculated for the whole site and for the gilgai elements.

Grouping for Soil Water Hysteresis Analysis

To investigate possible hysteresis of cracking responding to drying-wetting conditions, the data sets of microhigh and microlow were further fractionated. The drying-wetting grouping is a relative classification depending on the soil horizons compared, and the criteria chosen. In this study we have selected the wetting-drying grouping based on soil water change between 10- and 25-cm depths within the soil moisture profile, because these layers are closest to the soil surface interfacing with the atmosphere, and vary the most with precipitation, infiltration and evapotranspiration. Additionally, soil water content in these layers showed the strongest relationship with soil surface cracking. Furthermore, results in numerical experiments conducted in five different-textured soils indicated that hysteresis had a major effect on near-surface conditions and diminished by depth (Mitchell and
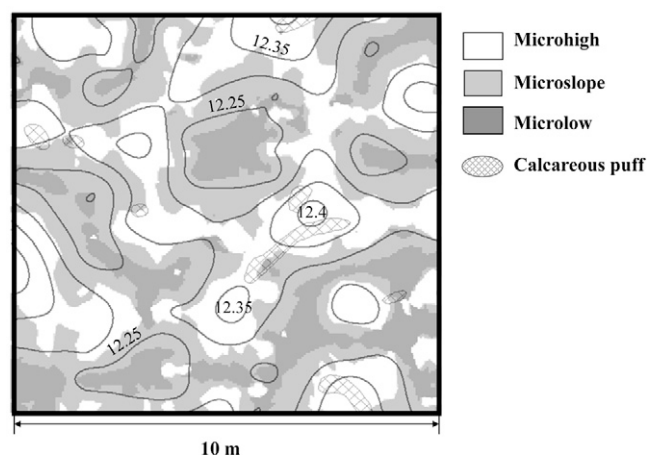

Fig. 1. Microtopography categories calculated from a digital elevation model (DEM) with 5-cm grid size. The locations of calcareous puffs digitized from the diagrams are shown for reference.

Mayer, 1998). Drying or wetting conditions were considered when the moisture difference between the upper and lower depth was negative or positive, respectively, and the difference was greater than the sum of averaged standard errors of the soil moisture measurements. Otherwise the observation was considered as a uniform moisture category. Uniform dry or uniform wet conditions were not differentiated because of large variation among the replicates of soil water measured in the field. The 18 dates of corresponding soil water and cracking measurements were used in the analysis.

Statistical and Other Analyses

Most analysis was performed on crack area, and crack area density (m^2 crack area m^{-2} soil surface) that is also called specific crack area (Yassoglou et al., 1994). Crack area density was calculated from the measured crack width and length assuming uniform width along each crack segment. Crack segments were spatially represented by their midpoint coordinates calculated after the fractionation by microtopography.

To quantify the crack depth-width relationship, empirical linear regression models were fitted based on data of the whole site, and data fractionated by microhigh, microslope, and microlow categories. On each crack measurement date, replicates of total crack depth were averaged within microtopography for each crack width category. Autocorrelation of the model residuals was check by calculating empirical semivariograms of the residuals. Six of the 42 crack measurement dates were excluded because field notes indicated that precipitation had washed in surface soil material and partially filled the cracks. These days were excluded because the depth measurements would not clearly reflect the process of shrinking-swelling.

S-Plus (Insightful, 2005) was used to conduct analysis of variance, linear least squares regression analysis, and to checking for spatial correlation of regression residuals by calculating an empirical semivariogram.

RESULTS AND DISCUSSION

The striking morphological differences observed in the profiles of gilgai elements by Wilding et al. (1990) were reflected also in the chemical and physical properties of a microhigh and microlow of the study site (Table 1). Total clay contents were high in both profiles peaking at a maximum of 56% at 36 to 60 cm in the microhigh and 54% at 101 to 134 cm in the microlow. Fine clay was greatest in the A horizons with 34 and 40% in microhigh and microlow, respectively. The COLE values of the microlow were equal-to or greater than that of the microhigh at all measured depths similarly to findings by Yule and Ritchie (1980). A weak linear correlation was shown between COLE and fine clay content with $r^2 = 0.3$ ($n = 16$, $p = 0.02$) for the combined microlow and microhigh data set. The overall tendency corresponded to the findings of Anderson et al. (1973) and Schafer and Singer (1976) who reported positive linear correlations between fine clay and COLE.

As Wilding and Tessier (1988) noted, other chemical and physical components, such as organic matter, carbonates, sesquioxides, silica, and low activity clays can cement soil fabric, increasing cohesive forces and decreasing shrink-swell potential. Soil organic C was greater in the microhigh than in the microlow at 0 to 10 cm. But the A-horizon was 23 cm shallower in the microhigh compared with the microlow. The microhigh was calcareous through the whole solum with a sharp increase at 126 cm where COLE decreased abruptly from 0.15 to 0.09 cm m^{-1}. Calcareous puffs and "chimneys" of calcareous clays appeared to be pushed up along slickenside planes (Wilding et al., 1990). Some of the chimneys were off-centered in microhighs leaning to microslopes (Fig. 1). The microlow was non-calcareous to a 134-cm depth and CaCO$_3$ increased at 170 to 220 cm where COLE had a local minimum.

Exchangeable Na percentage was low (ESP ≤ 3) to a depth of 126 and 220 cm at the microhigh and microlow, respectively. Both profiles had only traces of total soluble salts (Soil Survey Staff, 1990). Considering possible spray of sea salt from hurricanes or tropical storms, there was only one tropical storm, Allison, which landed close to Victoria on the Gulf Coast in 1989. But this storm contributed little rain over the site. Thus we assumed no considerable sea salt spray and consequently no changes in soluble salt content during the 10-yr study.

Crack measurements from the 42 diagrams are summarized in Table 2. Crack area density of the whole site is presented in Fig. 2. Crack formation occurred most intensively in the summer and early fall. The most extreme cracking conditions were measured in June and July of 1998, with a maximum crack area density of

Table 1. Soil characteristics for the Laewest clay at microhigh and microlow positions.

Depth	Horizon	Clay-silt-sand	Fine clay	Organic C	CaCO$_3$	CEC†	ESP†	COLE†
cm		———————— % of <2mm————————				cmol$^{(+)}$ kg^{-1}	%	cm cm^{-1}
			Microhigh					
0–10	A1	52–25–23	34	2.83	3	48.3	TR	0.12
10–36	A2	53–25–22	26	1.04	4	45.0	TR	0.13
36–60	Bk	56–23–21	18	0.31	3	44.2	3	0.15
60–94	Bkss1	52–29–19	19	0.25	3	44.5	1	0.10
94–126	Bkss2	50–31–19	28	0.18	5	42.9	2	0.15
126–163	Bkss3	39–43–18	23	0.06	31	28.1	5	0.09
163–186	Bkss4	41–39–20	21	0.03	27	26.7	6	0.11
186–215	BCk1	43–37–20	23	0.04	24	26.4	7	N/A
215–380	BCk2	36–42–22	20	0.04	33	20.2	8	N/A
380–530	2C	14–22–64	8	0.03	12	9.1	8	N/A
			Microlow					
0–7	A1	49–28–23	40	2.46	0	45.0	TR	0.13
7–25	A2	49–29–22	40	1.44	0	44.9	1	0.18
25–43	A3	49–30–21	39	1.23	0	43.7	1	0.17
43–59	Bw	48–29–23	34	1.10	0	42.2	2	0.17
59–101	Bss1	49–29–22	38	0.88	0	43.3	2	0.15
101–134	Bss2	54–26–20	37	0.55	0	45.3	3	0.15
134–149	Bss3	52–29–19	23	0.36	1	44.7	3	0.14
149–170	BCkss	49–31–20	27	0.17	9	38.5	4	0.13
170–220	BCk2	43–35–22	29	0.07	19	29.9	4	0.10
220–280	2C	38–42–20	21	0.06	7	22.2	7	0.13

† CEC, cation exchange capacity; ESP, exchangeable sodium percentage; COLE, coefficient of linear extensibility.

Table 2. Summary of all crack segments measured at different gilgai elements during the 1989–1998 study period.

	Segment length			Width			Depth		
	†MH	MS	ML	MH	MS	ML	MH	MS	ML
Min.,cm	<1	<1	<1	<1	<1	<1	<1	<1	2
Max.,cm	77.9	82.1	85.6	7	7	7	140	140	107
Avg.,cm	13.3	10.7	8.9	1.7	1.5	1.6	41.8	36.6	51.0
CV	0.7	0.8	0.9	0.9	0.9	0.9	0.8	1.0	0.7
Skew	2.0	2.3	3.1	1.3	1.4	1.2	0.6	1.0	0.0
N	2906	1695	417	2906	1695	417	336	178	25

† MH, microhigh; MS, microslope; ML, microlow.

0.024 $m^2 m^{-2}$ although it was a wet year based on the annual precipitation. The smallest measured crack area density of the site was 0.00018 $m^2 m^{-2}$ on 20 Oct. 1992. Although the primary recharging period in Texas is typically between October and March, small open cracks were still observed in December of 1990 and January 1991 at the end of a normal precipitation year. Considering individual crack dimensions, the maximum horizontal crack width was 7 cm. The longest crack segment was 145 cm with a 4-cm width. The deepest crack segment opened to a 140-cm depth with a 7-cm width, and it was 93 cm long crossing microhigh and microslope positions. The maximum crack depth measured in the microlows was 107 cm, which corresponds to the depth of the subsurface bowl formation.

The maximum crack area density measured on the Laewest site (0.024 $m^2 m^{-2}$) was 3 to 10-fold less than that measured on Vertic Entisols in Greece by Yassoglou et al. (1994). The large difference in crack area density was surprising because the soils had similar COLE values (0.11–0.15), and COLE was even higher (0.18) at 7- to 25-cm depth in microlows of the Laewest clay. The difference in maximum crack area density might be attributed to an approximate 4% drier soil water content at the time of measurement, and to stress caused by intensive surface irrigation and cultivation before cracking on the measurement sites of Vertic Entisol.

Microtopography

The microhighs, microslopes, and microlows of the 100-m^2 study area covered 38, 43, and 19% of the site, respectively (Fig. 1). Microslope was the most extensive category of the plot just as it was the largest extent of a trench of Vertisols located about 10 km away from the Laewest site investigated by Wilding et al. (1990). Compared with the trench estimates, microhighs covered two times greater area and the microlows covered one third less of the plot than they were estimated from the trench.

The overall trend of the microtopography was similar to the findings of Klich et al. (1990) on microtopography of an argillic subsurface horizon boundary. In their study on Udertic Paleustalfs in East Central Texas, approximately 31% of the 10 m^2 area was classified as subsurface microhigh, 44% was transition zone, and 25% was subsurface microdepression or bowl. In Victoria, Australia, Knight (1980) mapped round gilgai developed on a sodic clay soil and found depressions covering 19% of the area, which was very similar to our site, but the microhighs were only about 10% of the Laewest site and the flat shelves covered 71% of the approximately 1000 m^2 site.
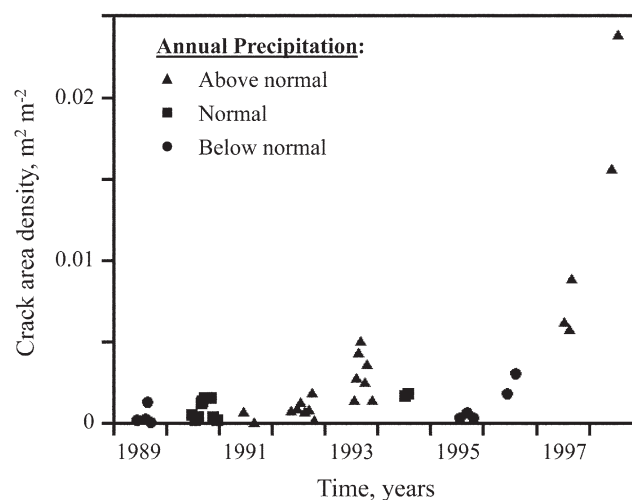

Fig. 2. Crack area density of the 100-m^2 site plotted for 42 measurement dates, and categorized by above normal, normal, and below normal annual precipitation.

Location of Crack Development

To illustrate the relationship with cracking and microtopography, the proportion of crack area for each gilgai category is shown for each crack measurement date (Fig. 3). Cracking occurred primarily on the microhighs 90% of the time, and once cracks appeared only on microhighs. Microslope cracking dominated the crack area only 3 out of 42 times (7%), which was also when crack area density was relatively low, <20 $cm^2 m^{-2}$, in 1991 and in 1995 (Fig. 2 and 3). Over 10 yr, the number of crack segments measured was almost 2 and 7 times greater on microhighs than on microslopes and microlows, respectively (Table 2). Crack density was also more abundant on microhighs in spite of the fact that the microlows had more fine clay (%) and greater COLE values than microhighs (Table 1).

In contrast, Thompson and Beckman (1982) reported visible cracks occurring more frequently and deeper in vegetated
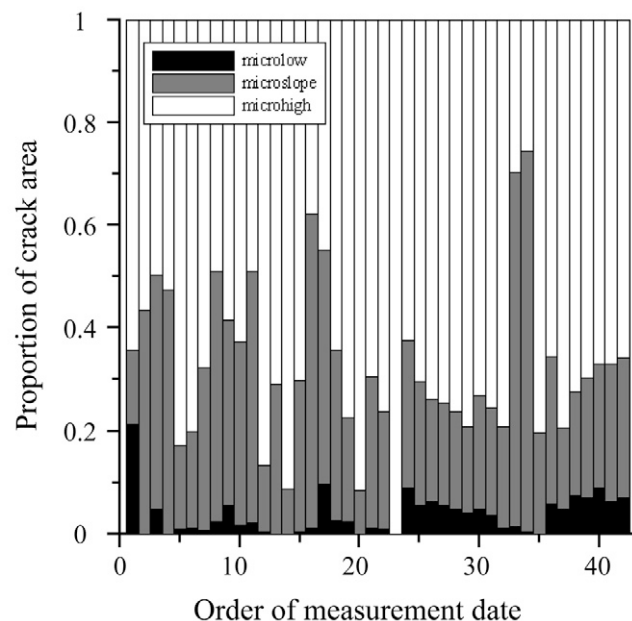

Fig. 3. Proportional distribution of crack area for gilgai elements on measurement dates.

depressions during prolonged drying periods of Black Earth with gilgai. Nonetheless, the microhighs of Black Earth began to dry out first, while water was still ponded in adjacent depressions. Differences between these conflicting observations might be attributed primarily to the difference in climate. East Australia, the location of the study, has an annual rainfall of 300 mm less than the Gulf Coast of Texas, thus it is possible that microlows of Black Earth dried out more than microlows of the Laewest clay.

The re-occurrence of cracks over time was found clustered in the same general locations. Based on field observations, cracks seem to close and re-open at exactly the same places sometimes, but the location shifts other times. We suspect that gilgai surface and subsurface features precondition the spatial clustering of cracks. Temporally, we speculate that a delicate balance of alternating location and recurring of cracks exists depending on the amount and intensity of precipitation and prior cracking conditions driving infiltration. The intensity of rainfall will partition water infiltration and preferential flow with the condition of existing cracks. On first hand, the more intense the rainfall, the more water will flow down the cracks and redistribute deeper in the soil than if it infiltrated through the surface soil matrix. Water flowing down the crack walls will wet the 0.01- to 0.02-m border zone around the cracks, which causes more rapid horizontal swelling than the bulk soil matrix (Favre et al., 1997). This heterogeneity of intensive wetting may cause an alternating crack pattern. Wells et al. (2003) found alternating location of crack opening and closing during multiple simulated rainstorms and drying cycles in laboratory conditions. In these experiments, the first cracks appeared at the driest soil regions, and desiccation along crack walls drove the cracking pattern. On the other hand, low intensity rain may cause the soil surface to swell and close in, leaving the

cracks open below the surface. If the soil incompletely wets before the next drying period, these subsurface cracks may re-open at the same locations.

Crack Width and Depth

Surface crack dimensions, length and width can be measured directly by hand or indirectly through image analysis. However, it is crack depth that contributes to preferential flow and subsequent redistribution deep into the soil. For modeling water infiltration and redistribution, estimating crack depth from more easily measurable crack characteristics would be useful. According to a study in India, crack depth was found positively and significantly correlated with crack width of Vertisols, but less correlated to crack length in cultivated field conditions by Bandyopadhyay et al. (2003).

On the 100-m^2 study area Laewest clay, there were 333 measurements of total vertical crack depth during the 10 yr. For the segments fractionated by gilgai, the descriptive statistics of total depth of crack segments are listed in Table 2. The linear least squares regression models fitted to the whole site, microhigh, microslope, and microlow categories are shown in Fig. 4. The residuals exhibited a pure nugget effect; thus, they were not spatially correlated. In general, crack depth showed positive and highly significant linear correlation with crack width for the whole data set and for data fractionated by gilgai position. This general tendency was in agreement with Bandyopadhyay et al. (2003). According to microtopography, the strongest correlation (r^2 = 0.57, n = 23, p < 0.001) and steepest slope of 17.85 were found in microlows, compared with microhighs with slope of 11.25 (r^2 = 0.49, n = 120, p < 0.001) and microslopes with slope of 14.24 (r^2 = 0.51, n = 75, p < 0.001). However, the regression models for individual gilgai categories were not significantly different from each other at α = 0.1; therefore, the total depth–width relationship was not microtopography specific. The hysteretic effects of drying and uniform soil moisture conditions described in the *Materials and Methods* section were also tested. The fitted regression lines for drying and uniform conditions were not significantly different at α = 0.1 level with sample size of 19 and 28 in microhighs, and of 9 and 6 in microlows, respectively. The large variation observed in crack depth for each crack width category was thought to be related to slickensides and variable wetting-drying dynamics in the subhorizons.

Dynamics of Soil Moisture-Surface Cracking: Microtopography

In general, horizontal shrinkage in the Laewest clay, characterized by surface crack area density, showed an inverse relationship with gravimetric soil water content that was strongest with soil water content measured at the 10- and 25-cm depth. However, gilgai microtopography had a major impact on this relationship (Fig. 3 and 5). Microhighs had 4 to 5 times greater crack area density than microlows when cracks were extensively developed, for example in 1997 and 1998, and more than 10 times greater occasionally, when cracking was limited by moisture conditions. Similar observations of more cracks concentrating in microhighs than microlows were made by Spotts (1974) on a Burleson clay (Texas) monitored over about 2 mo, and by Amidu and Dunbar (2007) conducting a field electrical resistiv-
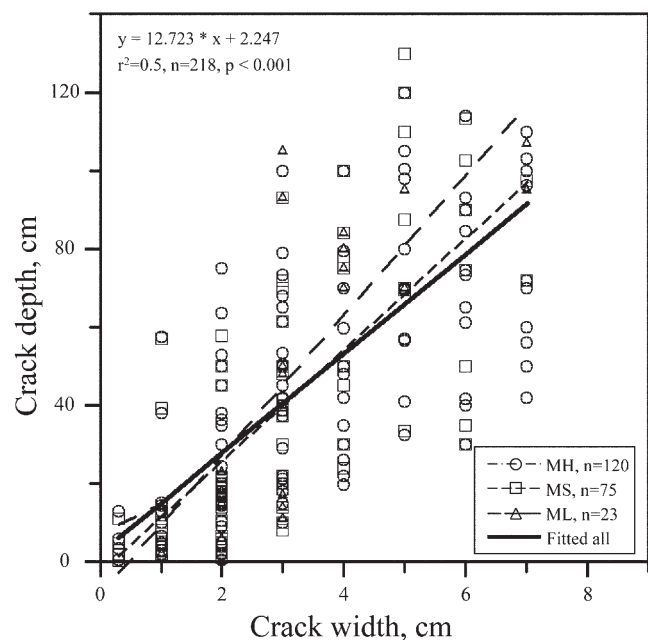

Fig. 4. Linear correlation between vertical crack depth and surface crack width based on measurements taken on microhighs, microslopes, and microlows. Crack depth data was averaged for each crack width category within a gilgai element for each day. MH, MS, and ML symbolize microhigh, microslope, and microlow, respectively.

ity survey on Houston Black clay in Texas over 1 yr.

On average, microhighs were drier than microlows in the upper 1 m (Table 3). Based on all 50 measurements of soil moisture, microlows were the same moisture or wetter than microhighs 98% of the times. The greater wetness in microlows seems to be systematically related to less cracking. Although soil water content was consistently greater in microlows of Laewest clay, this difference was only 2 to 3% on average (Table 3). The question is whether this difference in moisture content is the only factor responsible for the usually large difference in cracking of microhighs and of microlows. In addition to being wetter, the root system of plants may also reduce cracking in microlows. Although more dense vegetation of microlows can contribute positively to evapotranspiration and increase drying of microlows (Wilding et al., 1990), the anchoring of the root system and better soil structure may affect adversely the development of cracks (Mitchell, 1991).
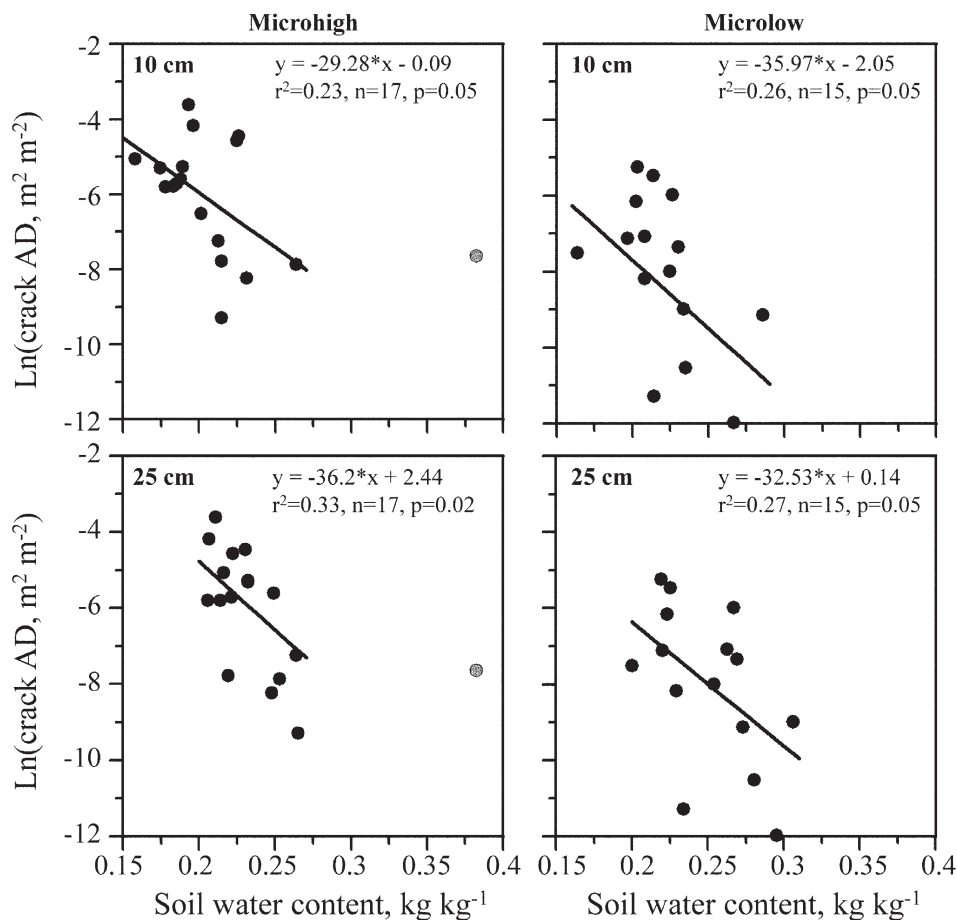

Fig. 5. Linear regression models were fitted to log-transformed surface crack area density (AD) versus gravimetric soil water content measured at the 10- and 25-cm depths on microhighs and microlows. On the graphs of microhigh, the gray-colored data point was considered an outlier, and was not included in the models.

Dynamics of Soil Moisture-Surface Cracking: Hysteresis

Initial graphs of crack area density as a function of soil water content indicated two distinct trends on microhighs (Fig. 5). Because of these trends, we expected some effect of hysteresis on soil cracking. To analyze the effect of soil water hysteresis on cracking, data sets of crack area density on microhighs and microlows were further fractionated based on moisture differences within the soil moisture profile. Drying, uniform and wetting profile conditions were assessed by comparing soil water content at 10 to 25 cm of soil moisture profile based on moisture samples taken on 18 dates and grouping by criteria described in the *Materials and Methods* section.

Out of the 18 dates, there were mainly drying (10 in microhighs and 11 in microlows) and uniform moisture conditions (6 in microhighs and 7 in microlows) measured. One measurement day (20 Oct. 1992) represented a clear wetting condition in both microhighs and microlows (Fig. 5 and 6). However, the wetting process was not represented well enough in this data set for analysis because only one crack measurement corresponded with the wetting condition.

Linear least squares regression models were fitted to log-transformed crack area density data as a function of gravimetric soil water content for drying and uniform conditions. Taking drying and uniform soil moisture conditions into account, significant improve-

ment was found for surface cracking and soil water content measured at 10-cm depth in microhighs and little improvement in microlows (Fig. 6). Although the sample number in each group was small, there was a significant trend with better linear correlation for drying ($r^2 = 0.69$, $n = 10$) and uniform conditions ($r^2 = 0.43$, $n = 7$) at the 10-cm depth in microhighs. Results also indicated that hysteritic categories were less separable in microlows than in microhighs. In microlows, there was a significant linear correlation ($r^2 = 0.40$, $n = 9$) for drying conditions and none for the uniform category. Considering soil water content measured at the 25-cm depth, there were somewhat less significant correlations between log-transformed crack area density and soil water content for drying microhighs ($r^2 = 0.2$, $n = 10$, $p = 0.09$) and uniform microhighs ($r^2 = 0.54$,

Table 3. Summary statistics of soil moisture measured on 18 dates corresponding to crack measurements.

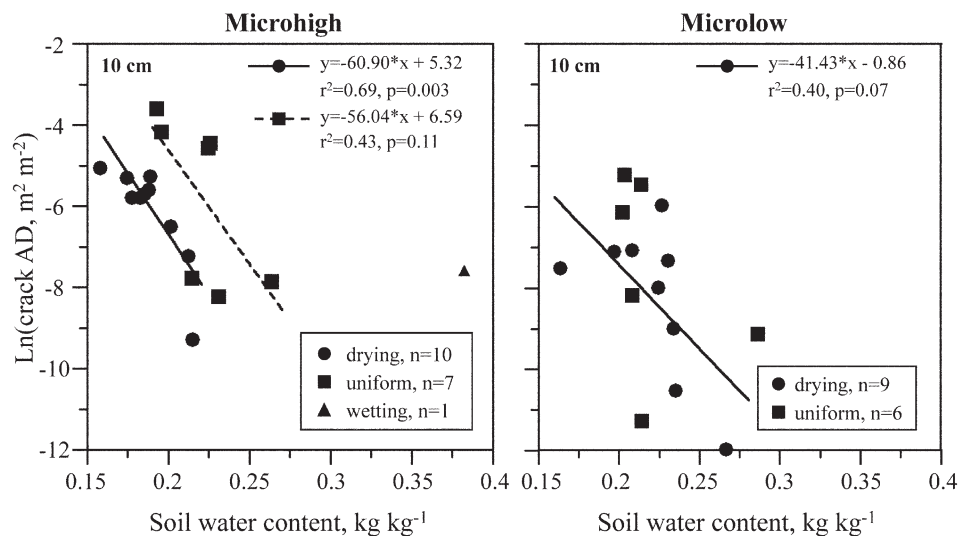| Depth	Microhighs				Microlows			
	Min.	Max.	Avg.	CV (SE†)	Min.	Max.	Avg.	CV (SE)
cm	——gravimetric %——				——gravimetric %—–			
10	15.8	38.2	21.2	0.23 (1.0)	16.3	46.4	23.7	0.27 (1.1)
25	20.6	33.0	24.0	0.14 (1.0)	20.0	36.9	26.4	0.17 (1.2)
50	20.9	33.7	24.1	0.14 (0.8)	21.2	37.0	26.9	0.17 (1.3)
75	20.9	33.0	25.7	0.14 (0.9)	21.2	37.9	27.6	0.17 (1.5)
100	21.0	33.5	26.5	0.12 (1.3)	21.2	33.6	28.5	0.14 (1.4)

† SE, standard error.

Fig. 6. Effect of hysteresis is shown in data sets fractionated based on difference in soil water content between 10 and 25 cm in the soil moisture profile. Linear regression models were fitted to log-transformed surface crack area density (AD) versus gravimetric soil water content measured at 10-cm depth in microhighs and microlows. No correlation was found for uniform moisture condition in microlows.

infiltration measurements in field conditions by Lin et al. (1998). In the temporal dynamics of cracking on the Laewest site over 10 yr, we found possible evidence of the effect of antecedent soil water before cracking. The first evidence was the surprising range of crack area densities corresponding to the same soil water content at 10 cm in microhighs (Fig. 5 and 6). In 1997 and 1998, outstandingly large cracking observations were associated with relatively high (19–23%) soil water contents. Possible sampling errors were ruled out based on careful scrutiny of standard errors and comparing data with field notes. Thus, the relatively higher soil moisture conditions measured on dates of great cracking extent is thought to be a composite effect of the prior long-term extreme wetting history, and more retained water in the soil pores due to hysteresis.

n = 7, p = 0.06). For 25 cm in microlows, there was a similar tendency in drying conditions (r^2 = 0.31, n = 9, p = 0.12) than for 10 cm; and no correlation for uniform conditions (n = 6). Less sensitivity of cracking to hysteresis exhibited in microlows may relate to a generally wetter environment in these soils.

Initial soil moisture, rainfall amount and intensity are considered important variables that determine rewetting and water redistribution after intense drying of a Vertisol (Amidu and Dunbar, 2007). Additionally, antecedent soil water content before cracking may affect the swelling–shrinking mechanisms as it was highlighted in laboratory measurements by Parker et a. (1982) and Tessier (1990), and depicted also by

Second, intense cracking seemed to follow periods of intense rainfall. Crack area density and precipitation data are summarized in Table 4 for each date when cracks and soil moisture were measured simultaneously. For the greatest measured crack area density of 18 dates (2 June 1998), rainfall accumulation for a 40-wk period (about 10 mo) was 810 mm, followed by 2 mo of drought with only a 19-mm precipitation. This drought included no rain in the last 4 wk before measuring the cracks. The next three dates with maximum cracking developed in a sequence over 2 mo of drought in the summer of 1997. This dry summer was preceded by a near record-breaking wet period related to El Niño and cooler than normal temperatures reported for Spring, 1997 (Maxwell, 1997; Read, 1998).

In summary, the high cracking densities of Laewest clay following high precipitation and subsequent drying indicated that the antecedent moisture condition might to be as important as the cracking potential and current soil moisture in predicting in situ soil cracking of Vertisols in the Texas Gulf Coast Prairie. This hypothesis is currently under investigation using this data set. The influence of antecedent soil moisture and repeated extreme rewetting of Vertisols in field conditions needs to be further explored by including long-term observations of different Vertisols under varying land uses, landscape conditions, and management practices.

CONCLUSIONS

Analysis of this 10-yr data set of Laewest clay has illustrated the true complexity of Vertisol cracking behavior in field conditions. Gilgai well developed under native prairie vegetation consisted of 38% of microhigh, 43% of microslope, and 19% of microlow in the study site. Crack development started dominantly and developed more extensively in microhighs, even though soil expansibility, characterized by the coefficient of linear extensibility

Table 4. Summary of surface crack area density (AD) at gilgai elements at dates of soil moisture measurement and sums of prior precipitation.

Dates	Crack AD	Weeks					
	MH/MS/ML†	0–2	2–4	4–8	8–12	12–24	24–48
	—cm² m⁻²—			—mm—			
11/01/1990	31/27/3	4	36	90	38	380	316
12/14/1990	4/1/0	0	21	42	65	445	304
08/28/1991	1/1/0	9	52	201	141	423	395
06/25/1992	15/7/1	0	61	284	189	362	478
10/20/1992	5/0/0	30	66	27	43	308	841
08/09/1993	52/16/9	24	5	228	225	396	436
09/30/1993	50/11/7	21	16	26	28	721	451
07/07/1994	33/8/3	0	102	138	56	159	285
08/01/1994	37/8/1	53	1	102	139	196	284
07/24/1995	3/5/0	60	9	143	31	139	531
09/07/1995	4/11/0	29	55	15	69	204	531
10/23/1995	7/2/0	2	5	135	122	250	305
06/14/1996	31/12/5	12	0	47	15	84	469
08/09/1996	64/11/8	2	4	151	12	65	391
07/11/1997	117/29/26	0	73	166	129	610	430
08/15/1997	105/31/21	51	1	8	166	763	348
09/02/1997	156/50/43	21	3	49	73	624	496
06/02/1998	273/96/54	0	0	19	51	165	594

† MH, microhigh; MS, microslope; ML, microlow.

(COLE), was greater in microlows. The more abundant cracking and three or more times greater surface crack area density on microhighs was likely due to generally drier conditions, 2 to 3% on average, in the near-surface and upper 1 m of the microhighs compared with microlows. In addition to the greater soil water content in the microlows, anchoring of plant root systems and stronger soil structure may also influence the balance between greater cracking potential and less actual crack formation in the microlows.

Considering re-occurrence of cracks over time, location of crack opening was found clustered in the same general locations. Sometimes, cracks closed and re-opened at exactly the same places, but other times, the location did shift. Temporal and spatial variability of rain pattern and water redistribution were thought to drive heterogeneous desiccation and rewetting at centimeter scales, which sometimes alternated crack locations.

Total crack depth exhibited highly significant linear correlation to surface crack width (r^2 = 0.5) based on all cracks measured. The effects of microtopography and hysteresis were not statistically significant; however the cracks developed in microlows were deeper on average.

Negative linear correlation between log-transformed crack area density and gravimetric moisture content was found strongest with soil water content measured at the 10- and 25-cm depths of microhighs and microlows. Although the overall correlation was weak (r^2 = 0.23–0.33), it was significant for both microhighs and microlows. Accounting for wetting-drying conditions based on soil moisture distribution within the 10- to 25-cm depths, the effect of hysteresis was more distinct in microhighs than in microlows. Stratifying data sets of crack area density according to hysteresis, the fitted linear least squares regression models were improved significantly, r^2 values increased up to 69%. Additionally, extreme weather conditions before large cracking indicated a surprisingly strong influence of antecedent moisture and long-term weather history on the surface cracking density of Laewest clay. Field studies are recommended to further investigate the mechanism and the effects of short- and long-term wetting and drying cycles on soil cracking processes, with special emphasis on antecedent soil moisture.

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